# A Light Higgs Boson from Gauge or Gaugino Mediation

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# Supersymmetric Higgs Bosons

- MSSM: Higgs signatures are often similar to the SM:

  $h^0$ is SM-like, $H^0$ and $A^0$ are difficult at the LHC.

- NMSSM: Higgs signatures can be much different

  if there is a light pseudoscalar $a_s$.

$$h^0 \;\to\; a_s\, a_s \quad \text{with} \quad a_s \to 2b,\; 2\tau, \ldots$$

$$BR(h^0 \to a_s a_s) \sim 1.$$

- This can help with fine tuning if $a_s \to 2\tau$. [ Dermîsèk+Gunion '05]

- Making $a_s$ light depends on couplings, SUSY breaking.

# A Light $a_s$ Pseudoscalar from a Singlet $U(1)_R$

- A light $a_s$ can arise from an approximate singlet $U(1)_R$.

  [Dobrescu+Matchev '00, Schuster+Toro '06]

- NMSSM Couplings:

$$W \supset \lambda\, S\, H_u \cdot H_d + \frac{\kappa}{3} S^3$$

$$V_{soft} \supset m_s^2\, |S|^2 + \lambda\, A_\lambda\, S\, H_u \cdot H_d + \frac{\kappa}{3} A_\kappa\, S^3.$$

- Approximate Singlet $U(1)_R \Leftrightarrow A_{\lambda,\kappa} \to 0$.

- This arises naturally if SUSY breaking is communicated primarily by gauge interactions.

# Gauge Mediation and the NMSSM

- NMSSM can fix the $\mu - B\mu$ problem of GMSB.
- GMSB + NMSSM has trouble with EW symmetry breaking.

  [DeGouvêa,Friedland,Murayama '97]
- Minimal GMSB $\Rightarrow \sqrt{|m_S^2|}$, $A_\lambda$, $A_\kappa$, $v \ll |\mu_{eff}|$.
- Minimization Conditions $\Rightarrow \frac{\kappa^2}{\lambda^2} \simeq -\frac{m_s^2}{\mu^2} \ll 1$.
- CP-even Higgs: $m_{h_1}^2 \propto \left(\frac{\kappa^2}{\lambda^2}\frac{g^2+g'^2}{2\lambda^2} - 1\right)$.
- Need $\lambda^2 \lll g^2 \Rightarrow$ singlet decouples, $BR(h^0 \to a_s a_s) \to 0$.

# Deformations of NMSSM Gauge Mediation

- A more negative $m_S^2(M_Z)$ can avoid this conclusion.
- Simple Options:

  1. New negative contributions to $m_S^2$ at $M_{mess}$ from coupling to messengers (without violating $U(1)_R$).

     [Ellwanger,Jean-Louis,Teixeira '08]

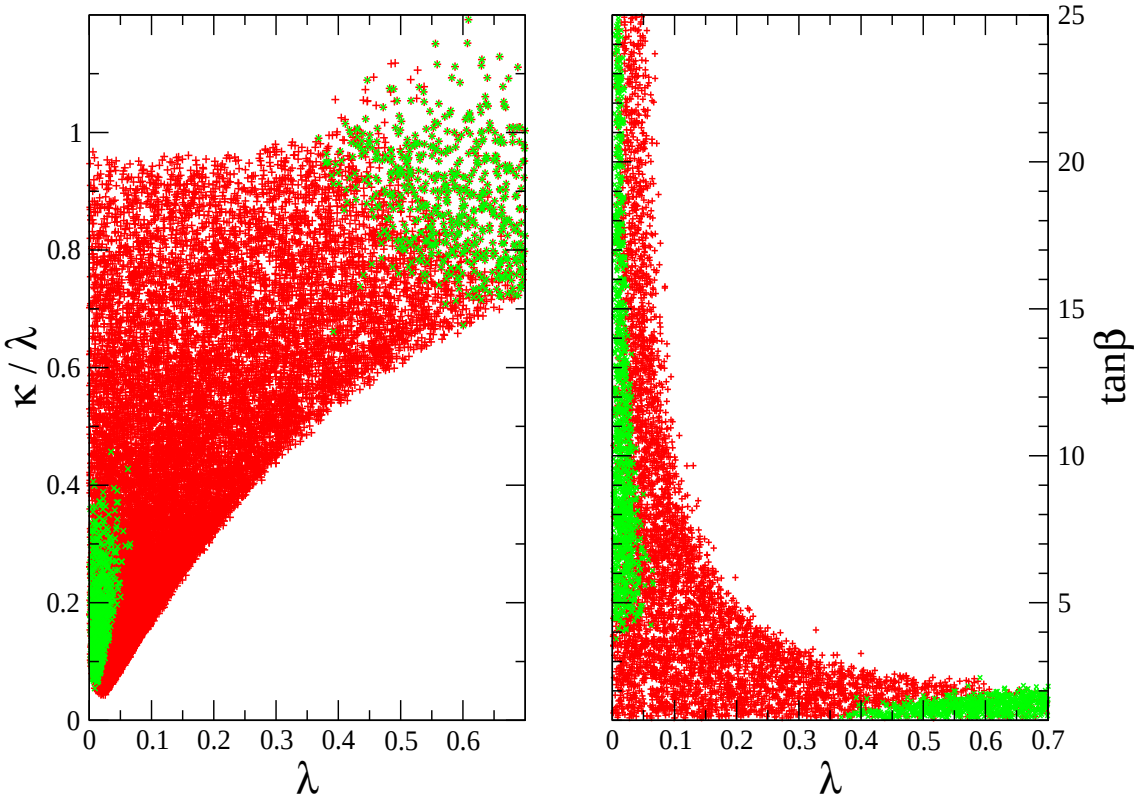
  2. Add $\mathbf{5} \oplus \bar{\mathbf{5}}$'s coupling to $S$:

$$W \supset \xi_D \, S \, D \, D^c + \xi_L \, S \, L \, L^c.$$

     Yukawa couplings drive $m_S^2$ negative through RG running.

     [Agashe+Graesser '97; DeGouvêa,Friedland,Murayama '97]

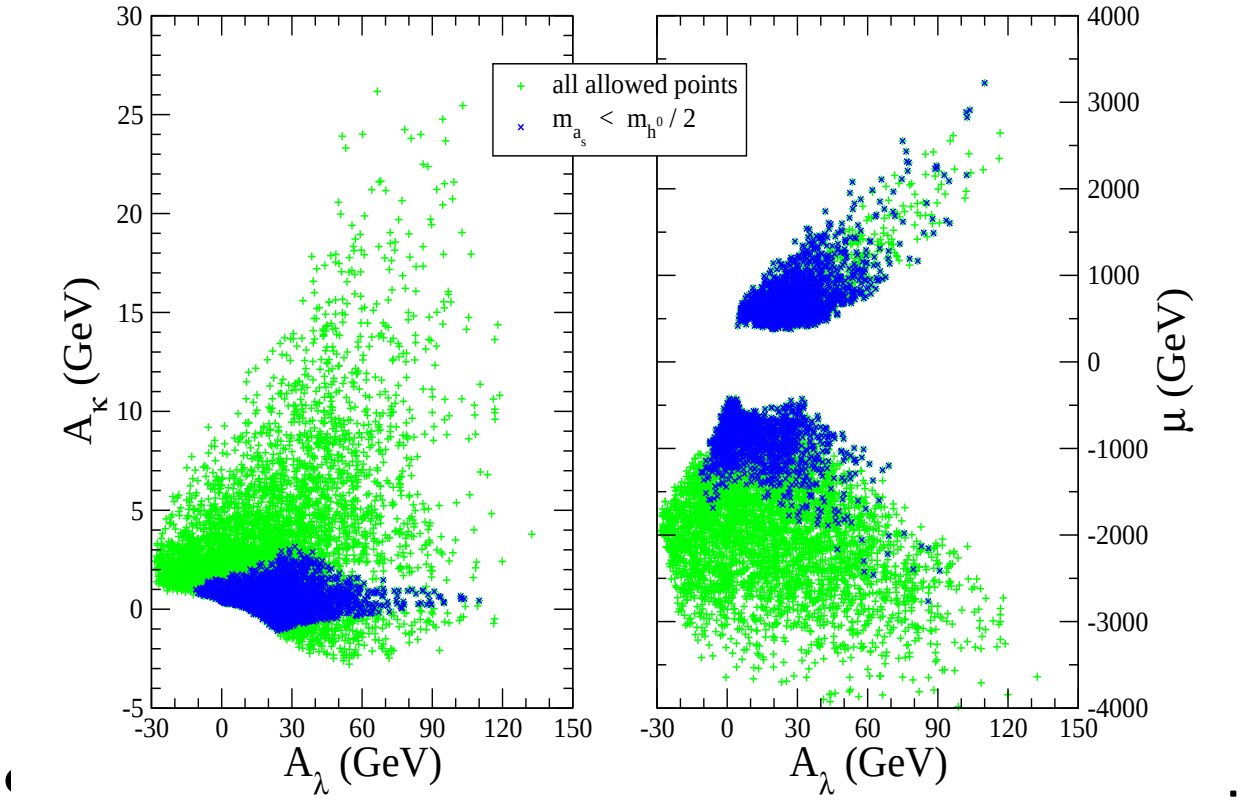
# Option #1: GMSB with $m_S^2$ Free




- $+$ = no Higgs constraints, x = Higgs constraints
- Two Regions: A. $\kappa \sim \lambda \gtrsim 0.4$, $\tan\beta \lesssim 2.5$

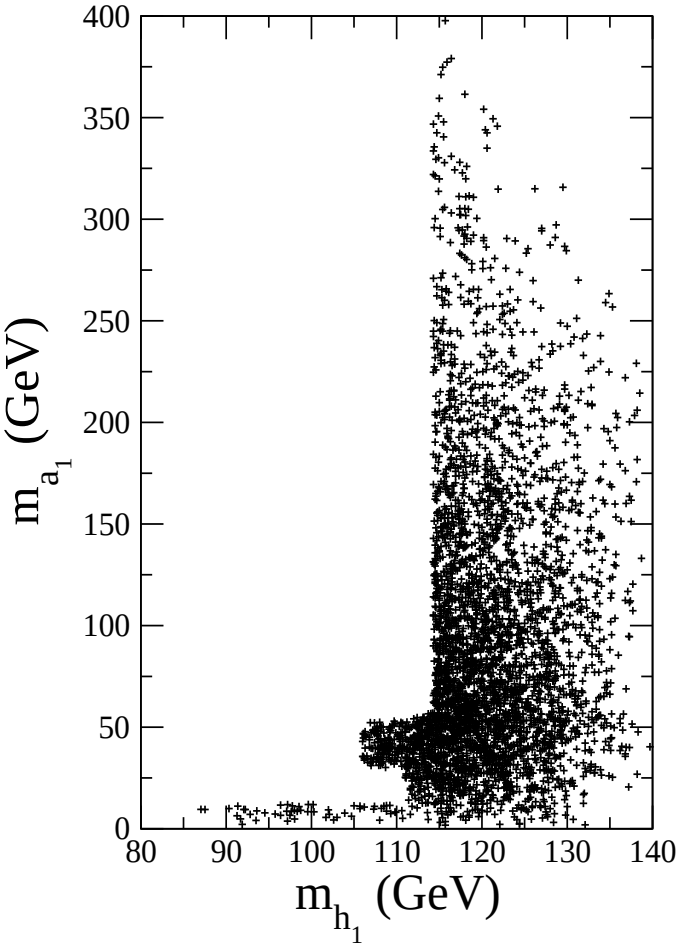
  B. $\kappa \ll \lambda \lesssim 0.05$, $\tan\beta \gtrsim 5$.

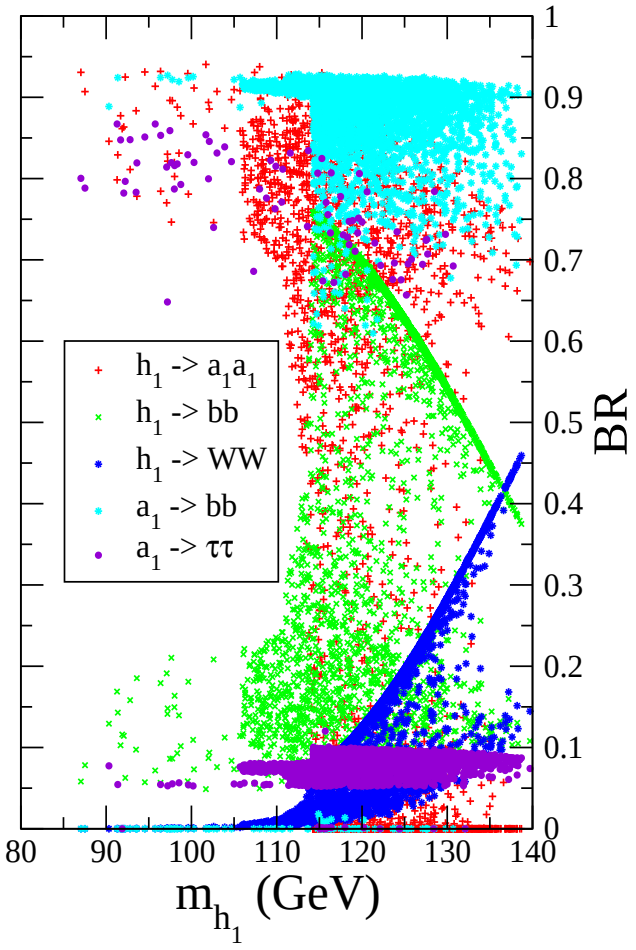
# Region A ($\lambda \gtrsim 0.4$): $A$ Terms




- Many points have $m_{a_s} < m_{h^0}/2$ for lower $M_{mess}$.
- $A_\kappa$ is more strongly constrained than $A_\lambda$.
- $|m_S^2|/\mu^2 \simeq 1$ for all these points.

# Region A ($\lambda \gtrsim 0.4$): Higgs Masses and Decays

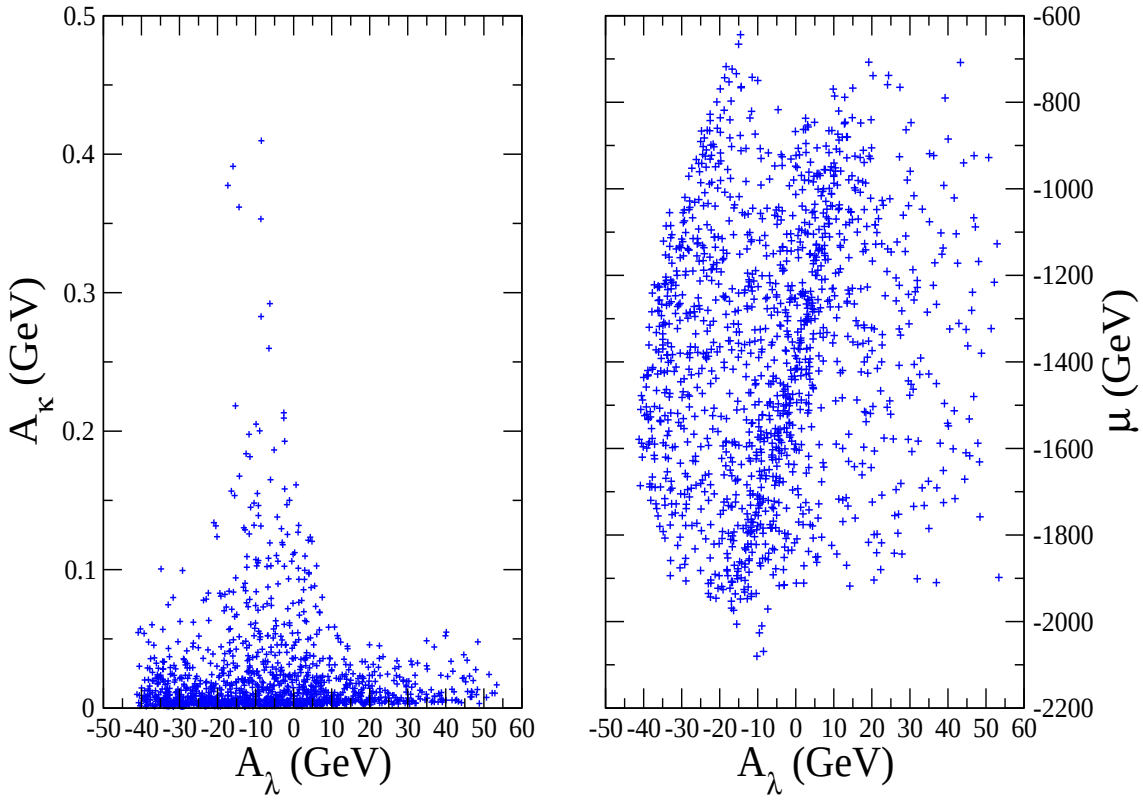



- .

- $h^0 \to a_s a_s \to 4b$ is common.
- $h^0 \to a_s a_s \to 4\tau$ is a bit tuned.

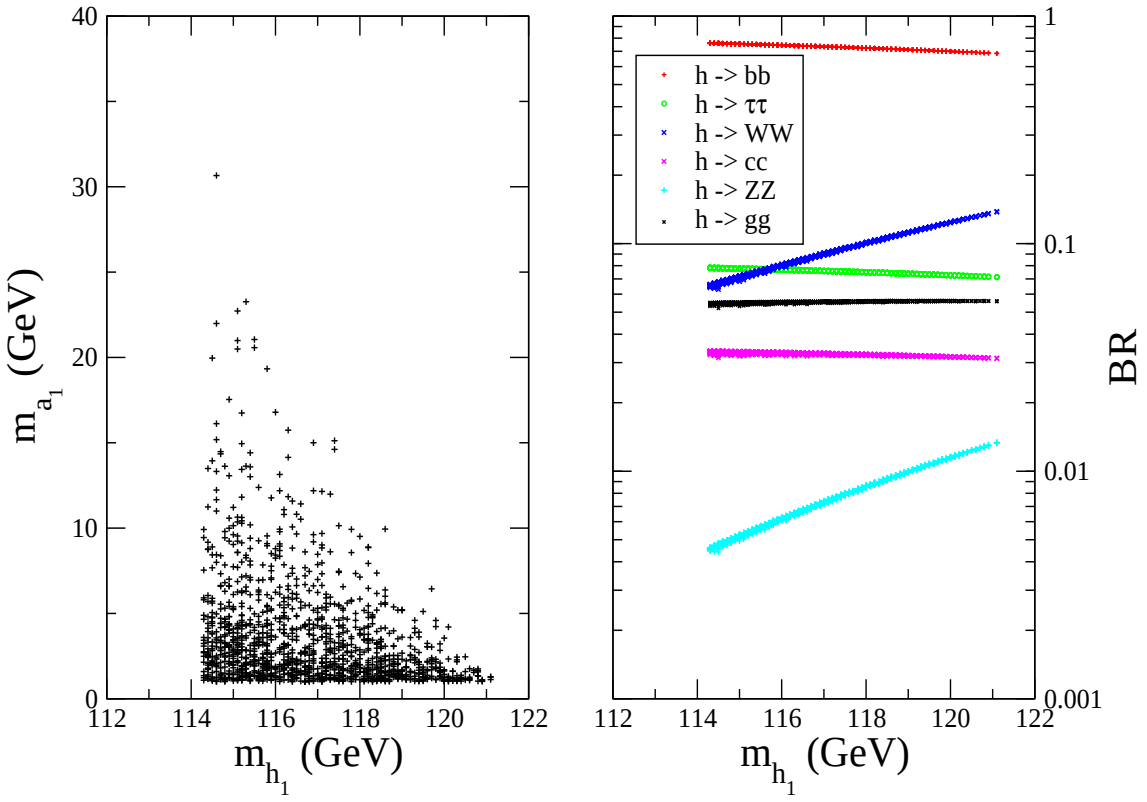
# Region B ($\lambda \lesssim 0.05$): $A$ Terms




- All points have $|m_S^2|/\mu^2 \ll 1$, $m_{a_s} < m_{h^0}/2$.
- $\kappa \ll \lambda \ll 1 \Rightarrow$ approximate $U(1)_{PQ}$.

  $\Rightarrow A_\kappa \ll A_\lambda \ll |\mu|$.

# Region B ($\lambda \lesssim 0.05$): Higgs Masses




- Pseudoscalar $a_s$ is always very light.
- It is also always decoupled: $BR(h^0 \to a_s a_s) \ll 1$.

# Some Analytic Results ($|\mu| \gg v, A_{\lambda,\kappa}$)

- Pseudoscalar $a_s$ Mass:

$$m_{a_s}^2 \simeq \frac{3\kappa}{\lambda}\mu\left(\frac{3\lambda}{\kappa}\frac{s_{2\beta}}{2}\frac{\lambda^2 v^2}{\mu^2}A_\lambda - A_\kappa\right).$$

- $BR(h^0 \to a_s a_s) \propto c^2$:

$$c \simeq \left(\frac{1}{2}\lambda^2\right)\left(\frac{\lambda}{\kappa} - 2\,s_{2\beta}\right)\left(\frac{\lambda}{\kappa} + s_{2\beta}\right)\frac{m_{h^0}^2}{2\mu^2}$$
$$+\left(\frac{1}{2}\lambda^2\right)\left[\frac{1}{2}\frac{\lambda}{\kappa}\frac{A_\kappa}{\mu}\left(1 - \frac{\kappa}{\lambda}s_{2\beta} - 12\,\frac{\kappa^2}{\lambda^2}s_{2\beta}^2\right) - 9\left(\frac{\kappa}{\lambda}s_{2\beta}\right)\frac{\lambda}{\kappa}\frac{A_\lambda}{\mu}\right].$$

Extends the results of [Dobrescu+Matchev '00] to include $A_{\lambda,\kappa}$.

# Option #2: GMSB with Vector-Like Exotics

- $W \supset \xi_{D_i} D_i D_i^c + \xi_{L_i} L_i L_i^c$, with $i = 1, \ldots, N_5$.

- $N_5 = 1$: $|m_S^2|/\mu^2 \ll 1$ obtains for $\xi_{D,L} < 1$.

  $\longrightarrow$ singlet decoupling (Region B)

- $N_5 \geq 2$: $|m_S^2|/\mu^2 \sim 1$ is possible.

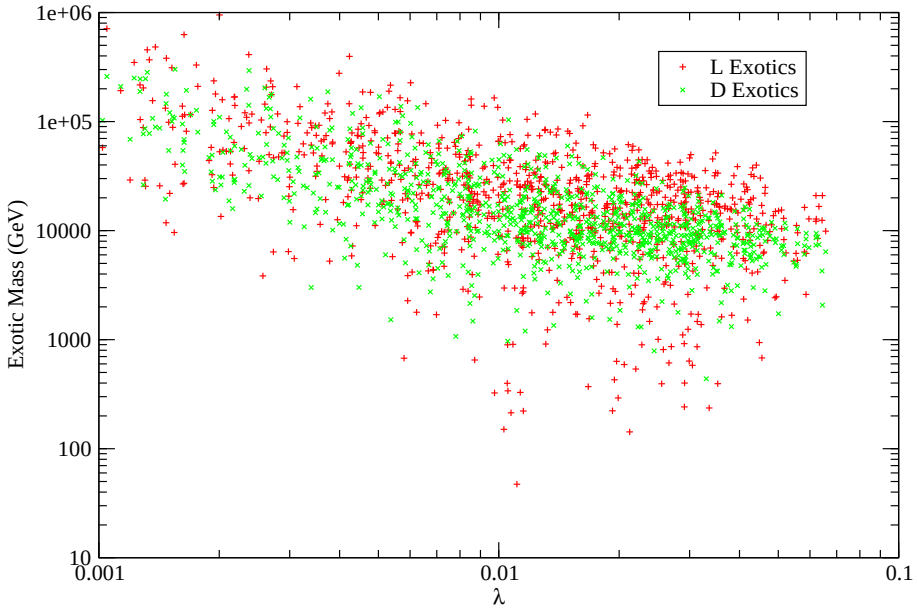
  $\xi_{D,L}$ communicates $U(1)_R$ breaking to the singlets.

  $\longrightarrow$ large $A_{\lambda,\kappa}$ and a heavier $a_s$.

- Higgs phenomenology is similar to the MSSM.

# Phenomenology of the Exotics

- Masses from the singlet VEV: $m_{D.L} = \xi_{D.L} \langle S \rangle$.




- These can decay through $d = 5$ operators.

- LHC signatures from punch-through to the muon chamber.

[Allanach *et al.* '01; Fairbairn *et al.* '06, Kang,Langacker,Nelson '07]

# Gaugino Mediation

- Idea: bulk gauge multiplets communicate SUSY breaking on a hidden brane to the MSSM matter fields.

  [Kaplan,Kribs,Schmaltz '99;Chacko,Luty,Nelson,Pontón '99]

- A singlet $U(1)_R$ also arises naturally in the NMSSM.

- Results are qualitatively similar to GMSB:

  – $m_S^2$ free leads to disjoint regions A and B.

  – Exotic $\mathbf{5} \oplus \bar{\mathbf{5}}$'s lead to either singlet decoupling or a heavy $a_s$ pseudoscalar.

- A light singlet neutralino can be the LSP.

# Summary

- NMSSM + gauge or gaugino mediation addresses the $\mu - B\mu$ problem in these models.
- Vanishing input $m_S^2$ makes EWSB challenging, and forces an approx. $U(1)_{PQ}$ and a decoupled singlet.
- An additional contribution to $m_S^2$ can fix this.
  A light coupled $a_S$ with $BR(h^0 \to a_s a_s)$ is fairly common.
- Extra exotics can help too, but don't keep $a_s$ light.
- $pp \to Zh^0$ with $h^0 \to a_s a_s \to 4b$ at the LHC?

  [Carena,Han,Huang,Wagner '07]